WINDS AND PRESSURES OVER THE SEA IN THE HURRICANE OF SEPTEMBER 1938

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ABSTRACT

The winds and pressures over the sea in the New England hurricane of September 1938 are reconstructed, making the meteorological ingredients available for a meteorological-oceanographic investigation of the record tide produced by this storm on the southern New England coast. The methods of analysis of the meteorological data are applicable to other hurricanes.

1. INTRODUCTION

The hurricane of September 1938 was among the most intense known to have occurred along the Atlantic Seaboard. This rapidly-moving storm reached the coastline of New England at the time of high tide, and as Brooks [1] describes it: "Towering surges on this combined astronomical tide and storm wave threw the sea to such heights that demolition was general along the exposed coast, and they came so suddenly that hundreds of persons, some of them at the shore to watch the fine surf, were engulfed and drowned." The purpose of this study was to develop reasonable estimates of winds and pressures over the sea in this great storm in order that they might be correlated with the observed tides which are the highest of record over much of the southern New England coast. The study was conducted in cooperation with the Corps of Engineers and was initiated in connection with their investigations on possible protective works against hurricane tides at Narragansett Bay and other points on the southern New England coast. However, the results should also be of general interest to those investigating the problem of predicting the tides to be expected with hurricanes.

The basic data for this study consisted of barograph traces and autographic wind records for all land stations in the area from New England to Hatteras and ships' observation forms. Time-graphs of the sea level pressure and 10-minute averages of the wind direction and speed were prepared for each station. Original Weather Bureau maps and special studies of the storm (e. g. [1, 3, 12, 18]) have been used to guide the detailed examination of the storm. Since the storm occurred before the development of aircraft reconnaissance and radar for meteorological purposes, the analysis techniques are more indirect than those that can be used on more recent hurricanes.

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2. TRACK OF STORM CENTER

A detailed storm track (fig. 1), necessary as a reference point for the wind and pressure analyses, was taken from Pierce's maps [12] with certain modifications. The 1200 EST position was moved northward on the basis of more complete ship observations than were available to Pierce. The track was also altered slightly over New England in order to indicate the position of the pressure center only. For instance, the location of Pierce's center is closer to New Haven than to Hartford, although Hartford had the lowest pressure. The wind center did pass west of New Haven (the pressure center was to the east) which probably influenced his decision on the position of the storm center. In this study a separate wind center was found and its position relative to the pressure center determined by plotting the wind direction (relative to the pressure center) for both Hartford and New Haven every 15 minutes, or more often during rapid direction changes (fig. 2). The wind center was found to be 16 nautical miles southwest of the pressure center. It was assumed that this distance and direction between the centers would hold while the storm was over the ocean. This observed displacement of the wind and pressure centers has been compared with Shaw's [16] theoretical separation of the centers for a moving circular depression. The relationship for the displacement, d, given by Shaw is $d=\frac{C}{2\omega \sin \phi+\zeta}$, where C is the speed of movement of the storm, $2\omega\sin\phi$ the Coriolis parameter, and ζ the angular velocity of the storm. At 1500 EST the gradient wind was 96 m. p. h. at a distance of 50 nautical miles from the center (the radius of maximum wind), which gives an angular velocity of 46×10^{-5} rad. sec.$^{-1}$. If these values are used, the computed displacement is 18.7 nautical miles, which is in close agreement with the 16 measured from figure 2.

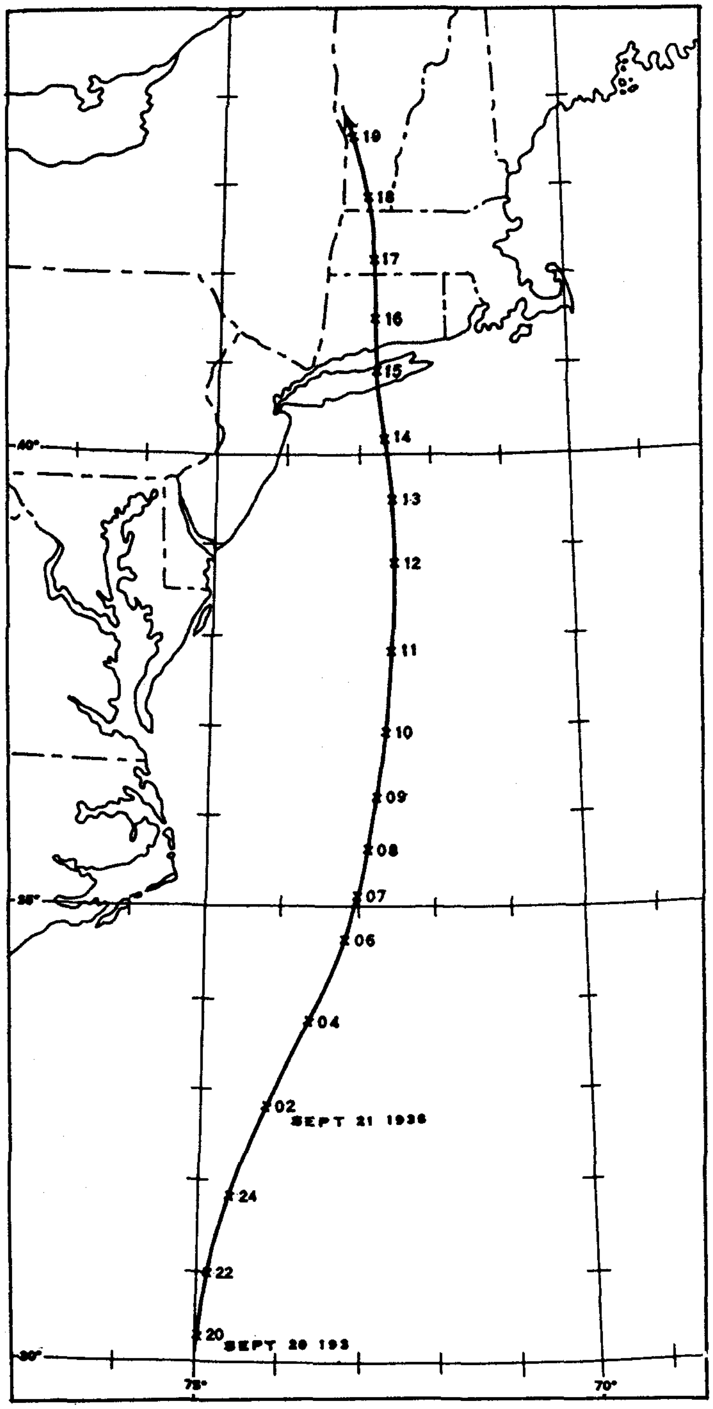

FIGURE 1.—Track of pressure center, hurricane of September 20–21 1938. Plotted times are in EST.

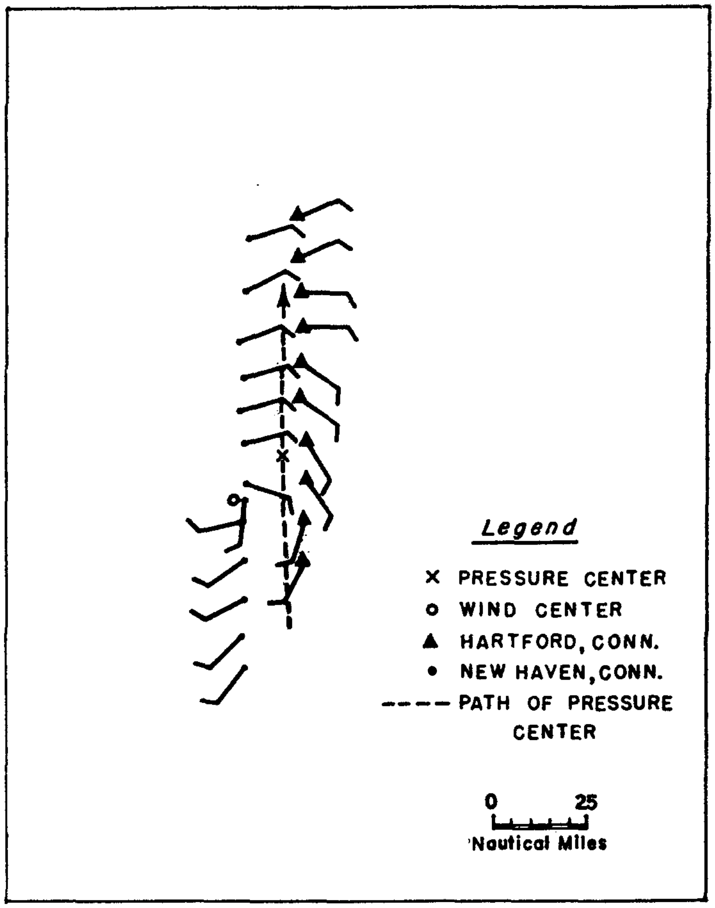

FIGURE 2.—Wind direction plotted relative to pressure center, near 1500 EST, September 21, 1938 at Hartford and New Haven, Conn. Pressure center (X) is reference point for plotting winds. Wind center (o) derived subjectively from plotted wind directions.

3. PRESSURE DISTRIBUTION

Pressure analyses were made hourly from 1200 EST through 1900 EST, and the maps for 1200, 1400, 1500, and 1900 EST are reproduced in figure 3. The pressure pattern was nearly circular through 1600 EST, but by 1900 EST it had become more elongated. Radial pressure profiles in the four cardinal directions were plotted from the maps for each hour, and the hourly continuity of these profiles was in turn used to adjust the analyses in areas of no data. Although the storm was over the ocean for the most part at 1200 and 1300 EST, ship reports taken to the north and west of the storm center at the 1200 EST standard observation time provide enough data for a fairly adequate analysis, together with continuity with later times when the storm was over land. Selected profiles along a line to the east of the pressure center, approximately normal to the direction of motion, are shown in figure 4; variation of the central pressure with time, derived from the profiles, is depicted in figure 5. The central-pressure determinations over land are considered reliable within a few hundredths of an inch, the estimates over the sea much less so, with the reliability more appropriately expressed in quarters of an inch. A central pressure of 27.75 inches at 1200 EST (fig. 5) is derived by extrapolating the pressure profile inward from the ship reports, of which 28.10 inches (corrected) by the *Birmingham City* was the lowest. The central-pressure curve in figure 5 is leveled off prior to 1200 EST, on the basis that the central pressure is also estimated at about 27.75 inches on the previous afternoon, with the storm center near 30° N. The lowest report at that time was 28.00 inches (whether corrected was not specified) from the *Indian Arrow*.

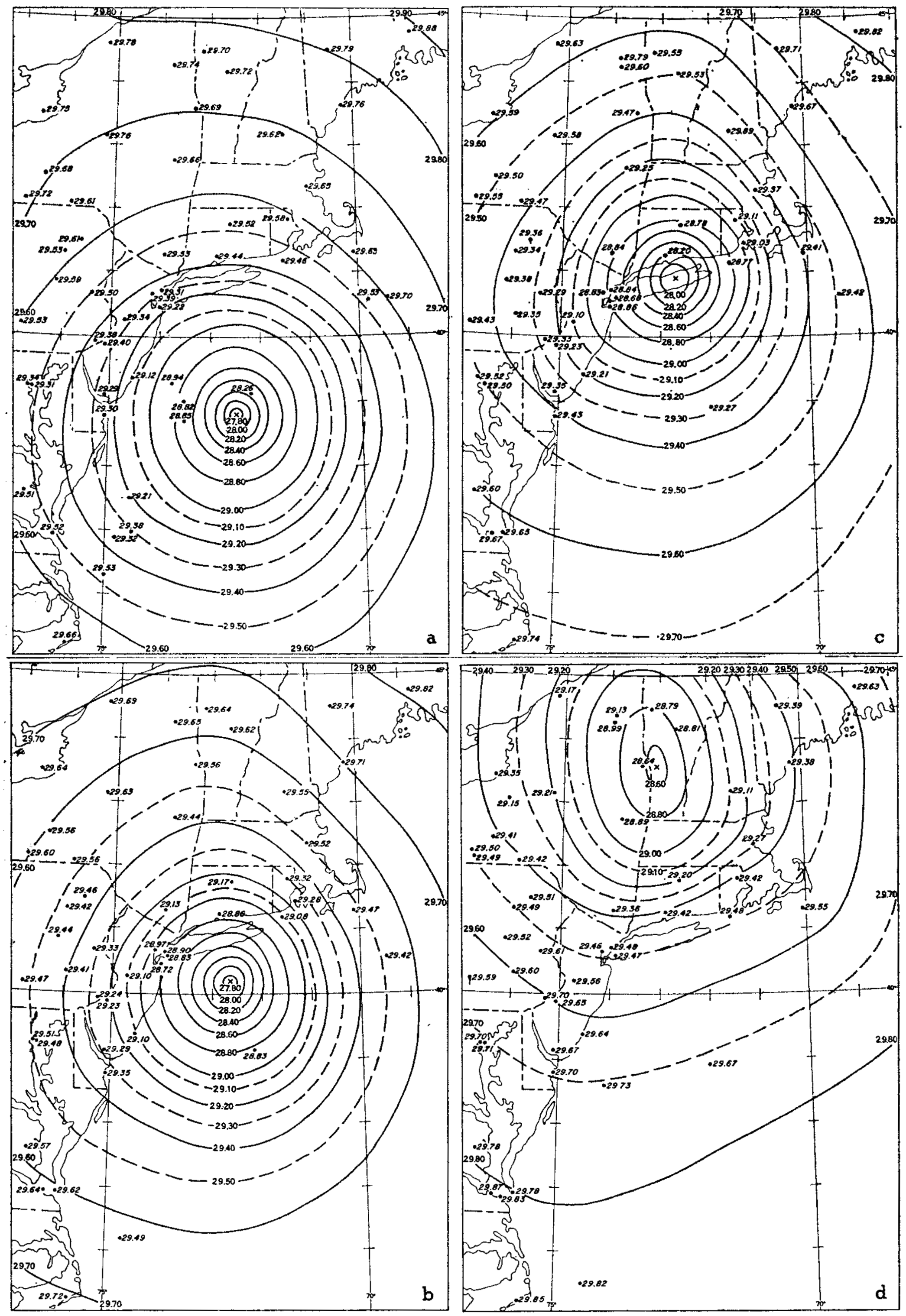

FIGURE 3.—Sea-level pressure (inches), September 21, 1938. (a) 1200 EST, (b) 1400 EST, (c) 1500 EST, (d) 1900 EST.

4. RADIUS OF MAXIMUM WINDS

Reid [13, 14] has developed a method for estimating the relative tide-producing potential of hurricanes over a particular part of the Continental Shelf as a function of the central pressure of the storm and of the radius to the maximum wind speed, R. The tide potential, by his method, is quite sensitive to R, principally because the larger the circle of maximum winds, the longer the fetch of strong winds in approximately the same direction. In the 1938 storm R is large and seems to vary somewhat around the storm. In the northern part of the storm, Hartford reached its maxi-

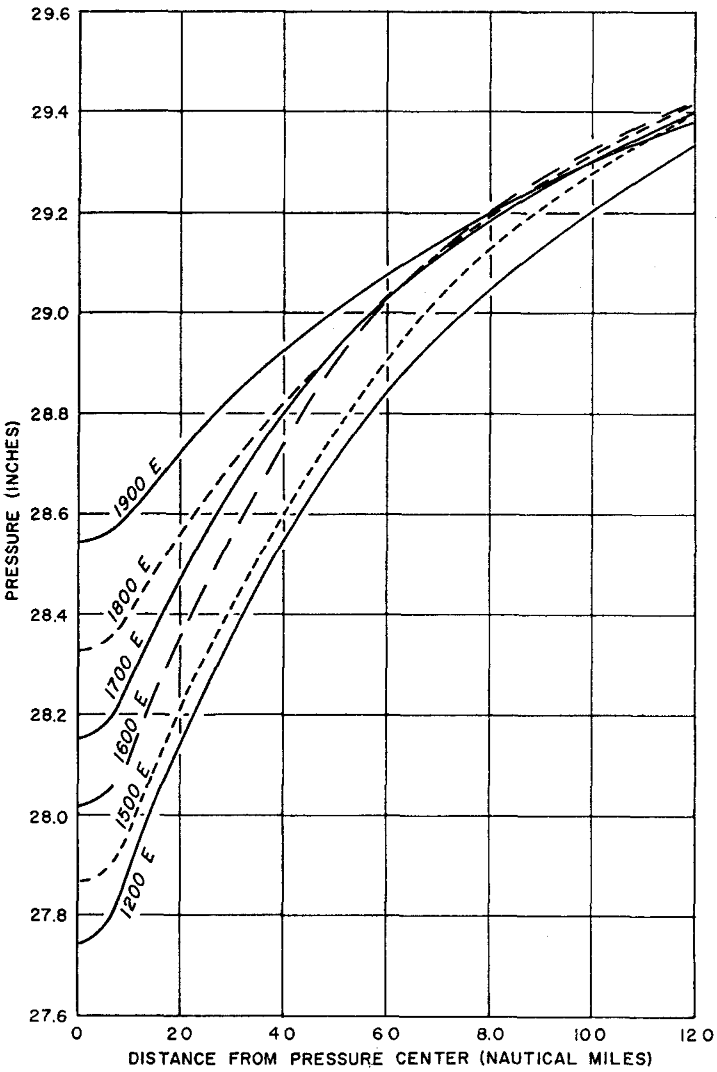

FIGURE 4.—Pressure profiles to east of center, September 21, 1938.

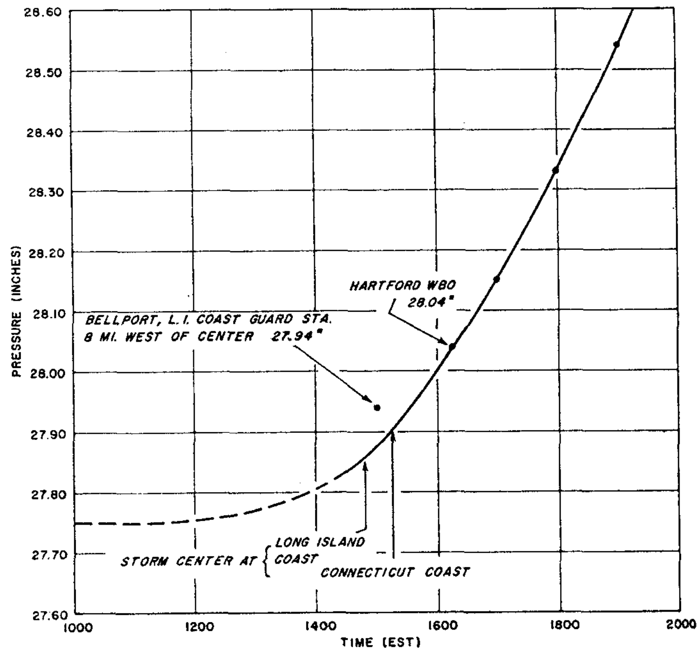

FIGURE 5.—Central pressure of the hurricane during September 21, 1938.

mum wind speed at a distance of about 50 nautical miles from the wind center. However after the storm had passed Hartford, the maximum wind occurred at a distance of 30 nautical miles from the center. The same pattern was shown at New Haven where the maximum speed was observed at about 43 nautical miles to the north of the approaching storm center and 30–35 nautical miles to the south of the center as it moved off. The second maximum was more difficult to distinguish, however. On the east side of the storm, where the highest winds occurred, there is an absence of stations between the wind center and about 60 nautical miles, and R was placed at the radius indicated by the computed gradient winds in this direction (figs. 6 and 7). Other evidence for a large R is a report of "calm" winds as far out as 30 nautical miles [1], and a report prepared by the Corps of Engineers [3] in which the region of strongest winds was estimated at a distance of 64 nautical miles to the right of the storm center. There were more ships reporting in the storm area on the afternoon of the 20th, when the storm was at 30° N., than on the 21st. At this time R appears to have been roughly the same (50 nautical miles) or slightly less than at the coast of New England. These ships reported Beaufort force 12 as far out as 60 nautical miles from the center, with speeds decreasing beyond that point. Since all speeds greater than 75 m. p. h. are lumped into the force 12 classification, a close determination of R at this time is not possible.

5. WIND SPEED DISTRIBUTION

A wind distribution over the ocean is required for computing the energy available to produce the storm surge and waves. Since data were not sufficient over the ocean for preparation of isotach analyses directly, it was necessary to deduce the patterns indirectly from pressure analyses and from the winds at land stations.

Gradient winds were computed from the pressure profiles to the east of the storm center, and an empirical relationship was established between these and the 30-ft. winds. The empirical relationship is intended to take care of both the difference between the computed gradient wind and the true wind at the gradient level [2] and the reduction of the surface wind by friction. The solid lines in figures 6 and 7 are the gradient wind curves. These curves for the hours 1400, 1500, and 1600 EST (fig. 6) are compared with the observed surface winds at Block Island, Providence, Nantucket, and New Haven. New Haven was actually north of the wind center, but three observations nearest the center were plotted on the

[2] Some of the assumptions used in computing the gradient wind which are not fulfilled in the hurricane are balance of forces, wind parallel to isobars, and radius of curvature of trajectory same as radius of curvature of isobar.

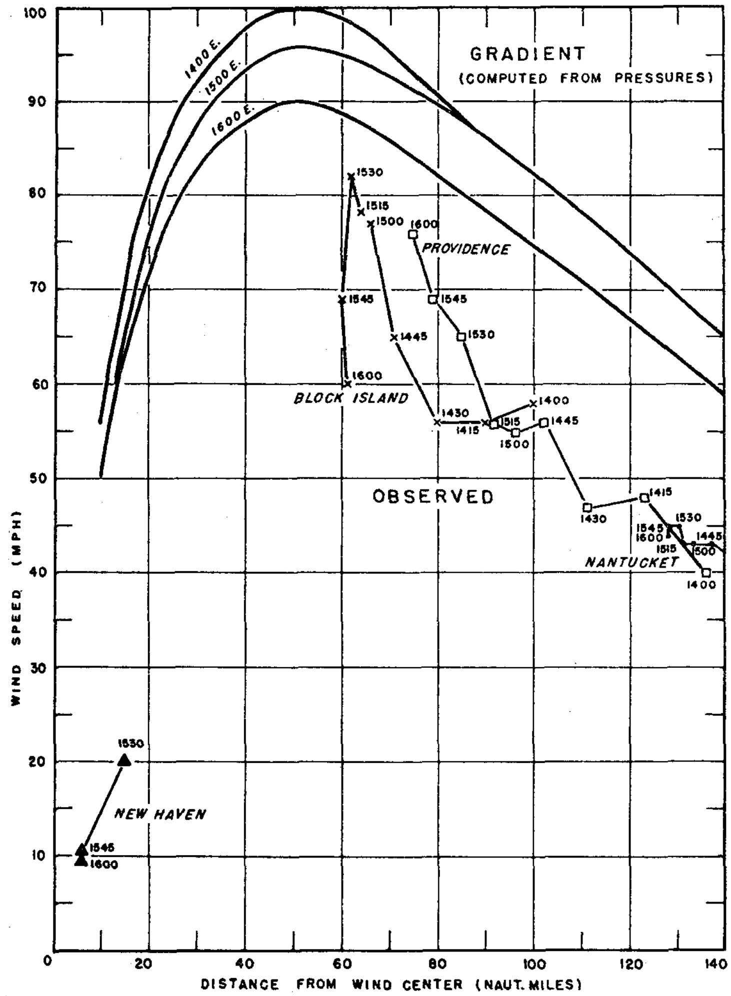

FIGURE 6.—Gradient and observed wind speeds, 1400–1600 EST, September 21, 1938.

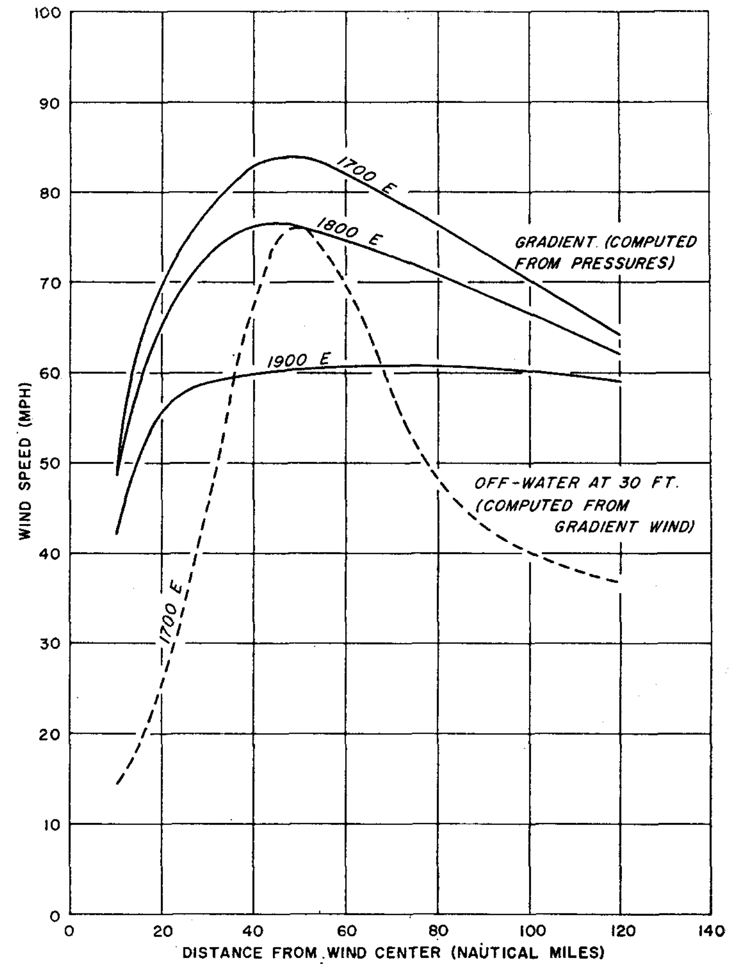

FIGURE 7.—Gradient and "off-water" wind speeds 1700–1900 EST, September 21, 1938.

assumption that the central values would not vary much around the storm. The height of the anemometers above ground varies at the four stations. The observed speeds were then adjusted to "off-water" (defined in the Appendix) values at 30 feet, using the wind reduction graph in figure 12 (explained in the Appendix).

The ratio of each of these adjusted wind speeds to the gradient wind speed at the same time was plotted against distance from the wind center (fig. 8), and a curve was drawn to fit the ratios [3] (solid curve). The relationship of the surface wind to gradient wind in the Florida hurricane of August 26–27, 1949 [8], adjusted to the R of the 1938 hurricane, is shown by dashed lines on the figure, and was used as a guide in drawing this curve. Profiles of the surface winds at 30 feet can be computed from the gradient-wind profiles at any time by using this relationship of the surface wind to the gradient wind. An example of such a profile is shown by the dashed curve of figure 7.

[3] The 1545 and 1600 EST wind speeds at Block Island were not considered representative and were not used to develop ratios. They were also disregarded in the analysis of figure 9. At this time the wind had veered to a direction from behind a hill higher than the anemometer.

To obtain an overall isotach pattern to supplement the above profiles to the east, a composite map of wind observations was constructed for a 2-hour period centered at 1500 EST. Mean 10-minute wind speeds, adjusted to a common basis,[4] were plotted relative to the pressure center and analyzed (fig. 9). The wind center from this analysis agrees with the wind center determined from the wind directions (fig. 2). The 1500 EST profile of the surface off-water wind at 30 feet (not shown but similar to the profile for 1700 EST in fig. 7) was used to help determine the analysis to the east in the area of no data.

Over-water isotachs, the end-product of the wind-speed analysis, are shown for 1200, 1400, 1500, and 1600 EST in figure 10. Winds prior to 1200 EST may be estimated by transposing the pattern for 1200 EST along the track (fig. 1). Over-water isotachs for specified times can be derived from the composite pattern of figure 9 by increasing the speeds by 12 percent to adjust from off-water to over-water (see Appendix) and by applying an additional small adjustment for filling of the storm between the time con-

[4] Adjusted to 30 feet above the surface and to the "off-water" frictional category by use of figure 12, and for filling of the storm by multiplying each speed by the ratio of the gradient wind at that time (from fig. 6) to the 1500 EST gradient wind.

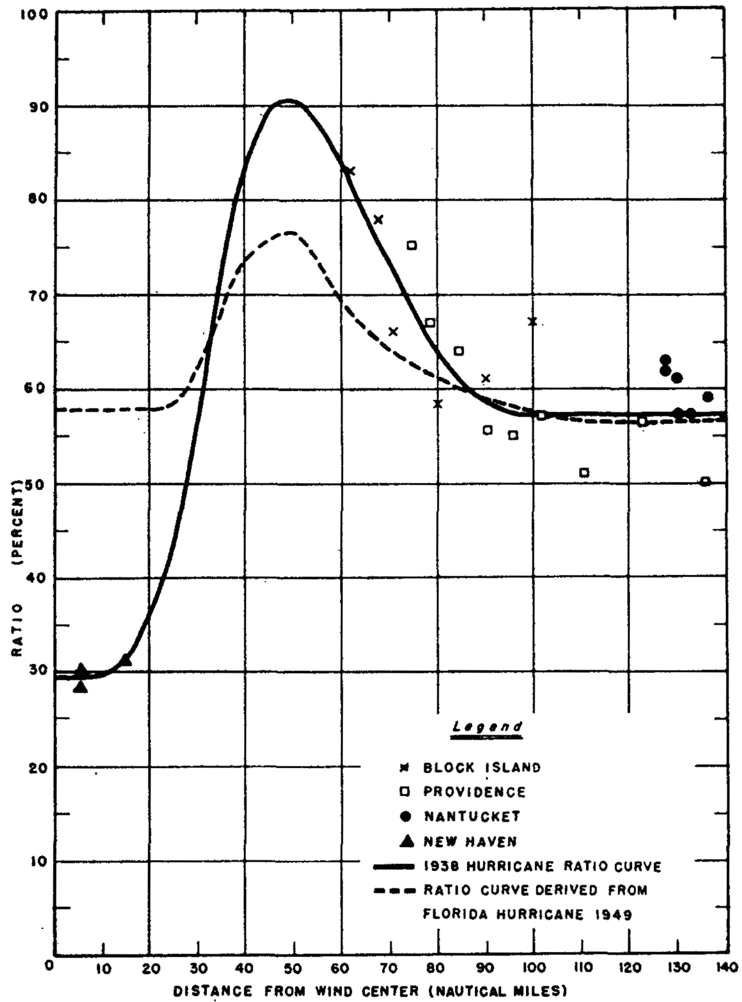

FIGURE 8.—Ratio of surface wind speed ("off-water" at 30 ft.) to gradient wind, September 21, 1938.

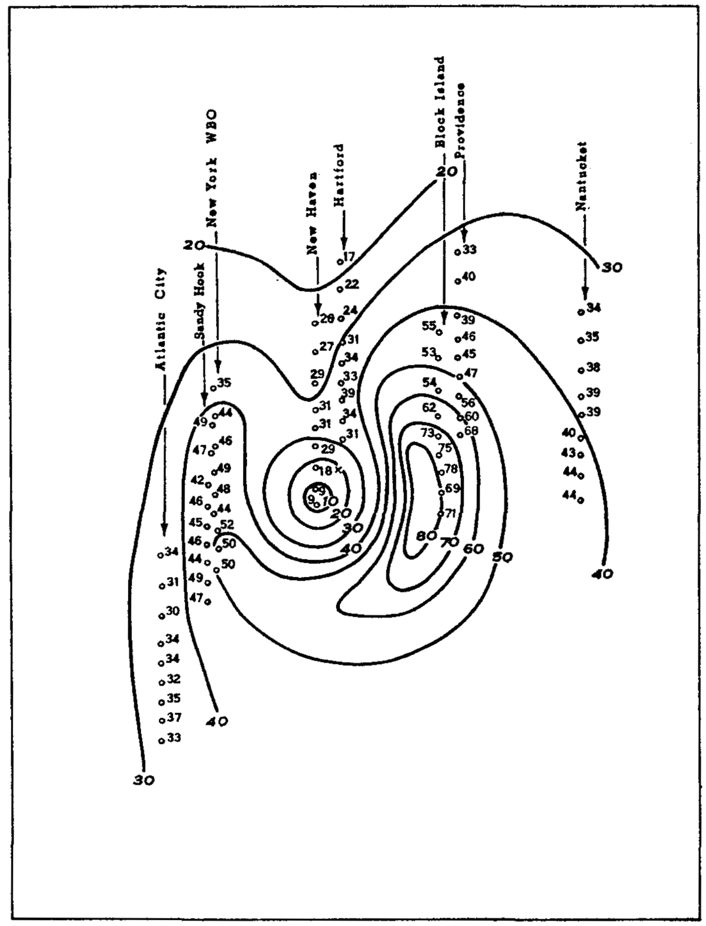

FIGURE 9.—Surface wind speeds (adjusted to 30 ft. off-water and 1500 EST intensity of storm) plotted relative to pressure center X, 1400–1600 EST, September 21, 1938. Speeds are in miles per hour. Distance scale same as figure 10.

cerned and 1500 EST, the reference time of the composite pattern. This was done for each time.

Ship and coastal wind speeds at the time of each map were plotted and the adjusted composite patterns were further modified to fit these. The coastal data were adjusted only for the reduction to the standard 30-ft. elevation. The 1200 EST isotach map is similar to Hughes' [5] mean pattern even though Hughes' data were south of 30° N. and did not include storms that had recurved.

6. WIND DIRECTION

Deflection angles (the angle between the wind direction and a tangent to a circle about the wind center) were examined in some detail in an effort to find a pattern through the storm as a whole that could be extrapolated from the regions of data to the regions of no data. Since the pattern was not well defined, the deflection angles for another great New England storm, that of September 1944, were added to expand the data. Average angles by zones from both New England storms were plotted on the same chart, together with the mean of the two storms (fig. 11), and a rough analysis was drawn to the data. This pattern is only approximately indicative of what would be observed in a hurricane over the ocean because of the effects of local topography, variations in friction from sea to land and from one place over land to another, height of the wind vane, inadequacy of 8-point wind-direction measuring systems, etc., in addition to the inherent variability of the wind direction. A large scatter in deflection angles seems to be typical for hurricanes. Johnson [9], working with high quality wind-direction data, showed a large scatter of the deflection angles throughout the August 1949 hurricane out to 70 miles from the center.

It appears from the right half of figure 11, and from Hughes' [5] mean wind-direction pattern, that use of a mean deflection angle of 25° outside R and 20° inside R would be satisfactory in correlating winds with surges in the 1938 storm. It also follows that, lacking a model of wind directions with a more substantial empirical or theoretical basis, further refinement of the wind direction along the critical fetch of maximum wind speeds in the shoreward quadrant of the storm is not warranted.

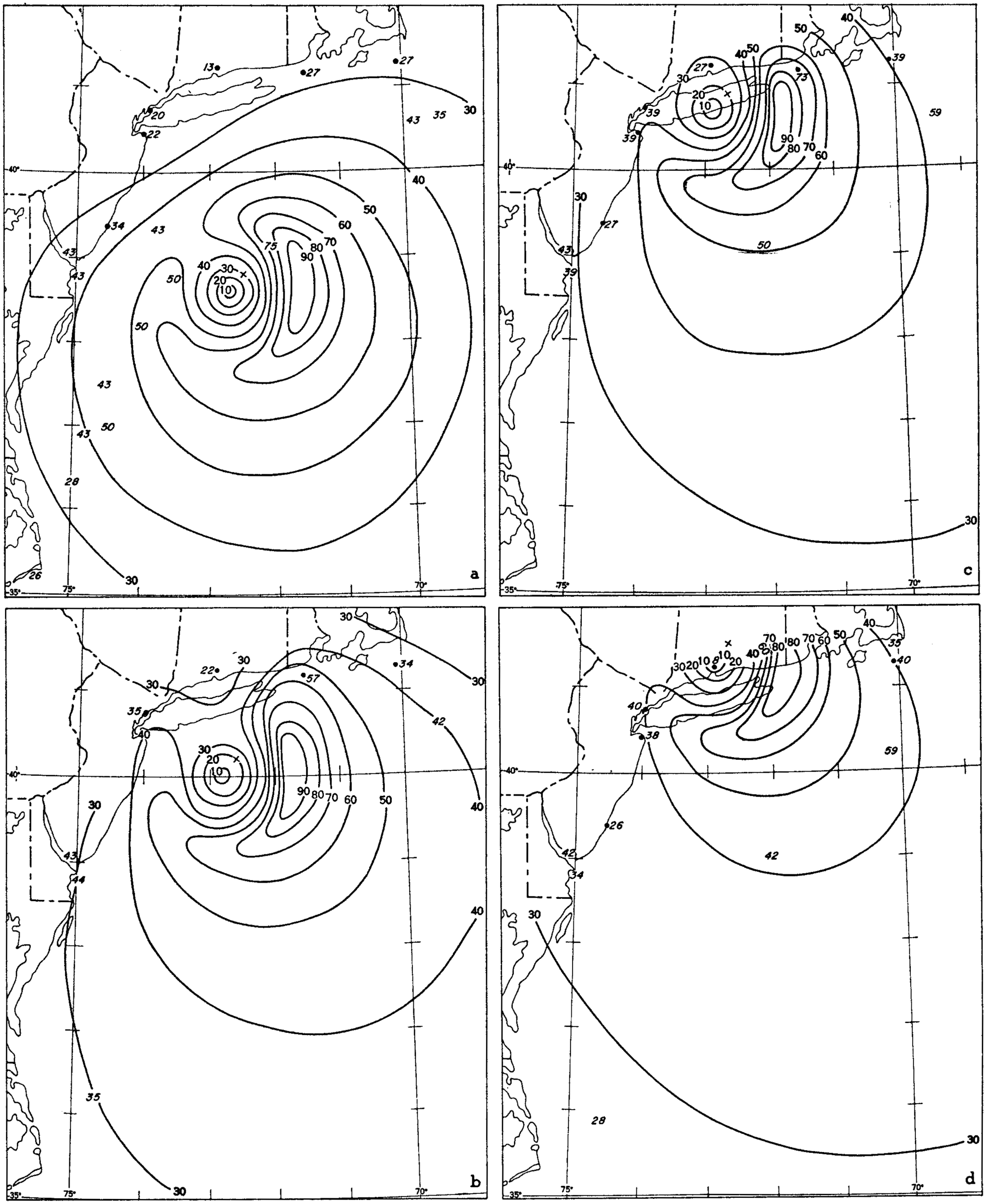

Figure 10.—30-foot wind speeds (m. p. h.) September 21, 1938. (a) 1200 EST, (b) 1400 EST, (c) 1500 EST, (d) 1600 EST. Data with dot positions are Weather Bureau Station observations, reduced to 30 feet. Data without dot positions are ship reports, unadjusted. X shows location of pressure center.

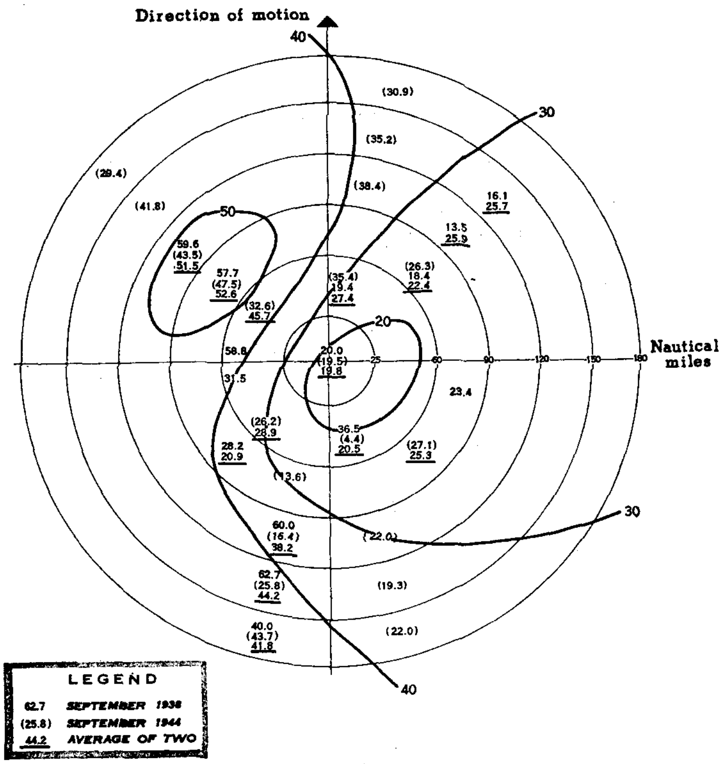

Figure 11.—Wind deflection angle (degrees). Data are means of zones outlined and are plotted at point of greatest concentration of observations in the zones.

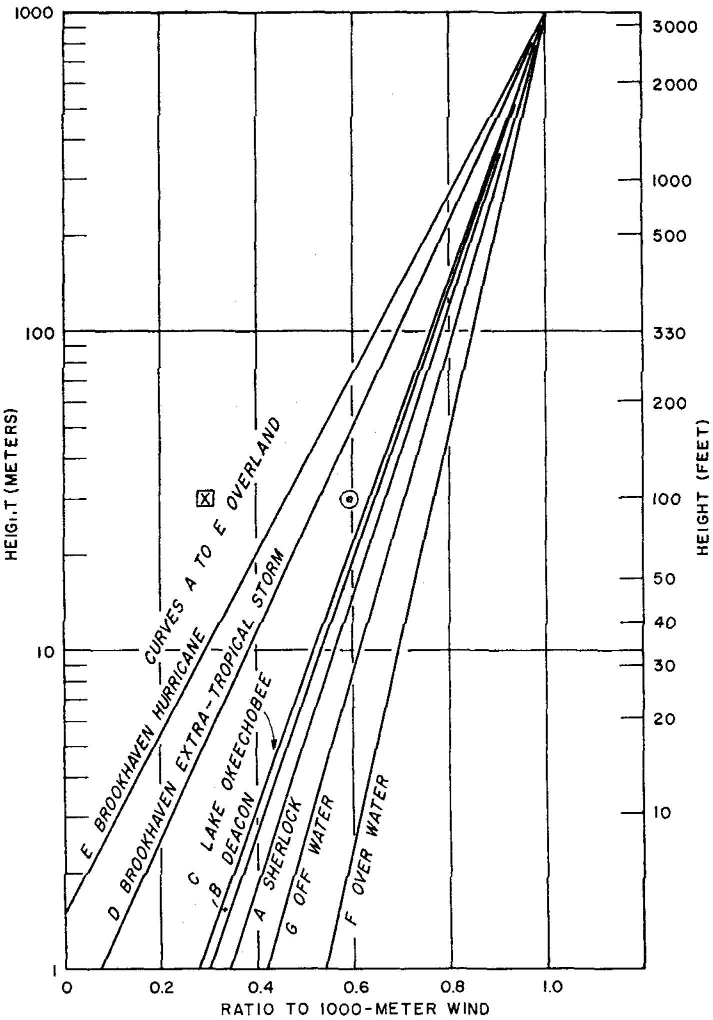

Figure 12.—Variation of wind speed with height and over various frictional surfaces. Derived from extrapolation of empirical data. Computed ratios (Rossby and Montgomery formula) are shown by ⊠ for rough, hilly country and ⊙ for open grassland.

7. SUMMARY

Estimates of the wind and pressure over the sea in the September 1938 hurricane have been derived by a series of deductions and are presented in the form of maps. The central pressure was slightly below 28.00 inches as the storm approached the New England coast and the radius to the axis of the maximum wind belt to the east of the center was about 50 nautical miles. Separate wind and pressure centers were identified. This storm was found to have a dynamic feature in common with other hurricanes analyzed by the Hydrometeorological Section, namely that the ratio of actual surface wind speed to the gradient wind speed computed from the pressure field increases from the outside of the storm to the radius of maximum winds. A rough composite wind direction pattern was developed.

APPENDIX

ADJUSTMENT OF WIND SPEEDS FOR HEIGHT OF ANEMOMETER AND FOR DIFFERING FRICTIONAL SURFACES

The wind-speed analyses presented in this paper are based directly or indirectly on the observed winds in the hurricane at varying anemometer heights and with varying frictional exposure. Three frictional categories are defined, winds over open water ("over-water"), winds impinging on a shore from open water ("off-water"), and winds over land, including winds blowing from land to sea at a coast ("off-land"). In studies of hurricanes at Lake Okeechobee, Fla., [6, 7, 8] it was found feasible to stratify the wind speeds into these three categories. It was assumed in the present study that at 1,000 meters the reduction of the wind speed by surface friction disappears, and therefore at this level the wind speed is the same above all frictional surfaces. Rossby and Montgomery [15] have shown that the height of the gradient level increases with wind speed. Therefore the gradient level was placed at the top of the range suggested by Byers [2] and Petterssen [10, 11]. Experimental data from various authors on the variation of wind with height were then applied to construct curves of the variation of wind speed from the surface to the 1,000-meter gradient level (fig. 12).

Deacon's [4] summary of experimental determinations by various investigators of the ratio of winds at a height of 100 meters to the 10-meter wind is reproduced in table 1.

TABLE 1.—*Ratios of 10-, 100-, and 1,000-meter wind speeds*

	V_{100}/V_{10}	V_{1000}/V_{10}	V_{10}/V_{1000}	Curve in fig. 12
Sale, Victoria, Australia	1.44	1.88	0.53	B
Cardington, Bedfordshire, England	1.48	1.96	.51	
Leafield, Oxfordshire, England	1.48	1.96	.51	
Quickhorn, Germany	1.71	2.42	.41	
Brookhaven Laboratory, Long Island, U. S. A. (extratropical storm).	1.83	2.66	.38	D
Brookhaven Laboratory (hurricanes)	2.20	3.40	.29	E
Akron, Ohio, U. S. A	1.66	2.32	.43	
United States (Sherlock's data)	1.39	1.78	.56	A

Source of ratios:
V_{100}/V_{10}: observed.
V_{1000}/V_{10}: extrapolated from V_{100}/V_{10} by use of logarithmic law:
$V_{1000}-V_{100}=V_{100}-V_{10}$
$V_{1000}/V_{10}=2\ (V_{100}/V_{10})-1$
V_{10}/V_{1000}: reciprocal of V_{1000}/V_{10}

For sources of observations, see Deacon [4], except for Brookhaven (hurricanes) which is from [17].

Also included is a ratio determined for hurricanes Carol and Edna of 1954 at Brookhaven National Laboratory, Upton, N. Y. [17]. All observations were made under conditions of either adiabatic lapse rate or moderate-to-high wind speeds. Smith and Singer [17] recently reported that the wind speeds at four levels from 37 feet to 410 feet on the tower at the Brookhaven Laboratory in hurricanes Carol and Edna showed a variation with height that fits both a logarithmic law ($V_1-V_2=K \log z_1/z_2$) and a power law ($V_1/V_2=(z_1/z_2)^n$), where the V's are the wind speeds at the corresponding heights, z. The logarithmic law was employed to extrapolate the experimental values of variation of wind with height up to the assumed gradient level of 1,000 meters and to compute ratios of 10-meter winds to 1,000-meter winds (table 1). Selected ratios were used to construct curves of variation of wind speed with height (fig. 12, curves A, B, D, and E). These are all curves for winds over land. The development of an additional off-land curve, C, is described later.

Of the wind factors listed in table 1, only one set, the second set of Brookhaven Laboratory data, was obtained in hurricanes. The others were measured at lower wind speeds, in the range from 20 to 45 or 50 m. p. h. The question arises of the applicability of the lower speed results to hurricanes. In hurricanes Carol and Edna at the Brookhaven National Laboratory there was no significant change in the ratio of the 37-ft. wind speed to the 150-ft. wind speed over the range of observed speeds, from 31 m. p. h. to 79 m. p. h. at the 150-ft. level. This evidence was given the greatest weight and it was assumed that the determinations of wind-speed variation with height in the lower speed range are reasonably applicable to hurricanes at similar sites.[5]

[5] There are other, and conflicting, indications on whether the ratio of the wind speeds at two heights varies with the wind speed. Comparison of curves D and E of figure 12 shows that at the Brookhaven site there was a greater relative variation of wind speed with height in the two hurricanes (curve E) than in the lower-speed extratropical storm (curve D). On the other hand, figure 30 of *Hydrometeorological Report* No. 32 [8] shows that the ratio of off-land wind speed to over-water speed at Lake Okeechobee increased as the wind speed increased. A logical deduction from this observation is that the relative variation of wind speed with height is less for higher speeds.

A curve of wind-speed variation with height (curve F, fig. 12) for open water was drawn simply by assuming that the wind speed at a height of 10 meters is 70 percent of that at the gradient level. The 70 percent factor is from the statement by Petterssen [10] that "At the surface, the actual wind over land is, on the average, about 40 percent of the geostrophic wind, whereas at sea it is about 70 percent." Petterssen also said [11] ". . . the analysis of the weather charts has shown that the ratio of the observed wind to the geostrophic wind is approximately as 2:3." Curve G, for off-water speeds, was constructed so that the speed at a height of 40 feet is 89 percent of the over-water speed at that height, the 89 percent factor being obtained from Lake Okeechobee studies [8]. Curves F and G appear to be reasonably placed with respect to the land surface curves (A to E). This indirect approach to constructing curves of wind-speed variation with height may be tested qualitatively by constructing an off-land curve in the same way. Thus, curve C for off-land wind was drawn such that the 40-ft. wind is 76 percent of the over-water wind at that level. That factor is obtained from figure 30 of *Hydrometeorological Report* No. 32 [8] which depicts ratios of off-land to over-water wind and is taken from the highest observed wind speeds (over-water, 81 m. p. h.; off-land, 62 m. p. h.). It can be noted that this curve lies very close to the curve for Deacon's Sale site (curve B).

Rossby and Montgomery [15] develop a formula (their equation 35) for the ratio of the anemometer-level wind to the gradient wind. This was not used in deriving the curves of figure 12 because knowledge is required of factors unavailable, such as the roughness parameter, z_0, and the angular difference in wind direction at anemometer and gradient levels. However some interesting comparisons can be made. Those authors obtained two typical solutions to the formula by substituting reasonable values: a ratio of 0.595 for open grassland and 0.293 for rough hilly country, both at a wind speed of 15.6 m. p. s., and an anemometer height of 30 meters. These ratios are plotted on figure 12 and compare well with the other data. The point for the hypothetical "rough hilly country" correctly lies to the left of curve E as the Brookhaven site is less rough than this.

From figure 12 the ratio of the wind speed over any frictional surface at any height to that over any frictional surface at another height may be obtained by reading off the respective ratios to the gradient-level wind and then taking the quotient of these ratios. (The variation in character of the surface from one site to another is so great that these ratios are far from precise. The principal justification for their use is that they are better than no adjustments at all). In the analysis of the 1938 hurricane, Block Island and Nantucket were considered off-water stations for all wind directions, and Atlantic City, Sandy Hook, New York WBO, and New Haven either off-water or off-land, depending on wind direction. Providence was off-land except over a very restricted sector in the direction of Narragansett Bay. Curve B of figure 11 was used for all off-land adjustments (arbitrary choice).

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